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# TOWARDS POWER-BASED CONTROL STRATEGIES FOR A CLASS OF NONLINEAR MECHANICAL SYSTEMS

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Abstract: In the present work we are interested on the derivation of power-based passivity properties for a certain class of non-linear mechanical systems. While for (non)-linear mechanical systems, it is of common use to adopt a storage function related to the *system's energy* in order to show passivity and stabilize the system on a desired equilibrium point (e.g., IDA-PBC (Ortega *et al.*, 1998)), we want here to obtain similar properties related to the *system's power*. The motivation arises from the idea that in some engineering applications (satellite orbit motion, aircraft dynamic, etc...) seems more sensible to cope with the power flowing into the system instead of the energy that for stabilization purposes, means to consider the systems's equilibrium the state for which the energy flow-rate (i.e., system's power) is minimal. In this respect, we recall first the power-based description for a certain class of (non)-linear mechanical systems given in (de Rinaldis and Scherpen, 2005) and then we give sufficient conditions to obtain power-based passivity properties, provided a suitable choice of port-variables. We conclude with the example of the inverted pendulum on the cart. *Copyright ©2006 IFAC*

Keywords: Nonlinear systems, Passivity-based control, Brayton-Moser equations, Lagrangian equations.

## 1. INTRODUCTION

In a previous work of the authors (de Rinaldis and Scherpen, 2005) an electrical interpretation of the motion equations of mechanical systems moving in a plane has been provided via the Brayton-Moser equations. In particular, it is proved that under certain generic assumptions the system's behavior derived from its Lagrangian function can be alternatively described through a power-based representation in an electrical fashion. It

can be viewed as an extension of the well-known analogy mass/inductor, spring/capacitor and damper/resistor for linear mechanical systems to a larger class of (possibly) nonlinear systems. *The double pendulum* and *the inverted pendulum on the cart* are the illustrative examples which have been studied and electrically interpreted as nonlinear RLC circuits.

We are here interested on exploiting this power-based description for such mechanical system class in order to achieve a new passivity property using

as port variables the external forces/torques and the linear/angular acceleration, and with the storage function being related to the system's power.

In section 2 we will first recall the fundamentals of Euler-Lagrange(EL) and Brayton-Moser(BM) equations in the standard form. Via the introduction of the pseudo-inductor the Brayton-Moser equations can be extended to a large class of non-linear mechanical systems, (de Rinaldis and Scherpen, 2005). This is reviewed in Section 3, and followed by the presentation of the main result. Taking inspiration from (Jeltsema *et al.*, 2003) we provide a method to generate storage function candidates based on the power. We give sufficient conditions to show the power-based passivity properties. We conclude the paper in section 4 with the example of the *the inverted pendulum on the cart* for which our passivity conditions have a clear physical meaning.

## 2. PRELIMINARIES

### 2.1 Euler-Lagrange systems (EL)

The standard Euler-Lagrange equations (e.g., (Ortega *et al.*, 1998)) for an  $r$  degrees of freedom mechanical system with generalized coordinates  $q \in \mathbb{R}^r$  and external forces  $\tau \in \mathbb{R}^r$  are given by

$$\frac{d}{dt} \left( \frac{\partial \mathcal{L}(q, \dot{q})}{\partial \dot{q}} \right) - \frac{\partial \mathcal{L}(q, \dot{q})}{\partial q} = \tau \quad (1)$$

where

$$\mathcal{L}(q, \dot{q}) \triangleq \mathcal{T}(q, \dot{q}) - \mathcal{V}(q) \quad (2)$$

is the so-called Lagrangian function,  $\mathcal{T}(q, \dot{q})$  is the kinetic energy which is of the form

$$\mathcal{T}(q, \dot{q}) = \frac{1}{2} \dot{q}^T D(q) \dot{q}, \quad (3)$$

where  $D(q) \in \mathbb{R}^{r \times r}$  is a symmetric positive definite matrix, and  $\mathcal{V}(q)$  is the potential function which is assumed to be bounded from below. Furthermore, dissipative elements can be included via the Rayleigh dissipation function as part of the external forces.

### 2.2 RLC-circuits: The Brayton-Moser equations (BM)

The electrical circuits considered in this paper are complete RLC-circuits in which all the elements can be nonlinear. The standard definitions of

respectively inductance and capacitance matrices are given by

$$L(i_\rho) = \frac{\partial \phi_\rho(i_\rho)}{\partial i_\rho}, \quad C(v_\sigma) = \frac{\partial q_\sigma(v_\sigma)}{\partial v_\sigma}$$

where  $i_\rho \in \mathbb{R}^r$  represents the currents flowing through the inductors and  $\phi_\rho(i_\rho) \in \mathbb{R}^r$  is the related magnetic flux vector. On the other hand  $v_\sigma \in \mathbb{R}^s$  defines the voltages across the capacitors and the vector  $q_\sigma(v_\sigma) \in \mathbb{R}^s$  represents the charges stored in the capacitors. From (Brayton and Moser, 1964) we know that the differential equations of such electrical circuits have the special form

$$Q(x)\dot{x} = \nabla P(x) \quad (4)$$

where  $x = (i_\rho, v_\sigma) \in \mathbb{R}^{r+s}$ ,  $\nabla = (\partial/\partial i_\rho, \partial/\partial v_\sigma)^T$ , and

$$Q(x) = \begin{bmatrix} -L(i_\rho) & 0 \\ 0 & C(v_\sigma) \end{bmatrix} \quad (5)$$

Furthermore the mixed potential function  $P(x)$  which contains the interconnection and resistive structure of the circuit is defined as

$$P(x) = F(i_\rho) - G(v_\sigma) - i_\rho^T \Lambda v_\sigma. \quad (6)$$

$F : \mathbb{R}^r \rightarrow \mathbb{R}$  and  $G : \mathbb{R}^s \rightarrow \mathbb{R}$  being the current potential (content) related with the current-controlled resistors (R) and the voltage potential (co-content) related with the voltage-controlled resistors (i.e., conductors, G), respectively. More specifically, the content and co-content are defined by the integrals

$$\int_0^{i_\rho} \hat{v}_R(i'_\rho) di'_\rho, \quad \int_0^{v_\sigma} \hat{i}_G(v'_\sigma) dv'_\sigma,$$

where  $\hat{v}_R(i_\rho)$  and  $\hat{i}_G(v_\sigma)$  are the characteristic functions of the (current-controlled) resistors and conductors (voltage-controlled resistors), respectively. The  $r \times s$  matrix  $\Lambda$  is given by the interconnection of the inductors and capacitors, and the elements of  $\Lambda$  are in  $\{-1, 0, 1\}$ .

### 2.3 Definitions

In order to introduce the electrical counter part of the position dependent mass we introduce the so-called *pseudo-inductor*. This is an inductor, but now relating the magnetic flux linkages to current and the voltage, which differs from the “usual” electrical case, i.e.,

$$\phi = f_\phi(x). \quad (7)$$

where  $\phi \in \mathbb{R}^r$  is the flux related to the inductors. This definition lead to the following implicit relation between voltage and current

$$v_\rho = \frac{d\phi}{dt} = \frac{\partial f_\phi}{\partial i_\rho} \frac{di_\rho}{dt} + \frac{\partial f_\phi}{\partial v_\sigma} \frac{dv_\sigma}{dt}. \quad (8)$$

Now, define the *pseudo-inductance matrix* and the *co-pseudo-inductance matrix* as

$$\tilde{L}(x) = \frac{\partial f_\phi}{\partial i_\rho}, \quad \tilde{M}(x) = \frac{\partial f_\phi}{\partial v_\sigma}$$

respectively, then (8) can be written as

$$v_\rho = \tilde{L}(x) \frac{di_\rho}{dt} + \tilde{M}(x) \frac{dv_\sigma}{dt}. \quad (9)$$

Similarly, we will consider a *capacitor* as a function relating the charge and the voltage, i.e.,

$$q_{\sigma j} = f_v^j(v_{\sigma j}), \quad j = 1, \dots, s. \quad (10)$$

By defining the non-negative capacitance matrix

$$C(v_\sigma) = \text{diag} \left( \frac{\partial f_v^j(v_{\sigma j})}{\partial v_{\sigma j}} \right), \quad j = 1, \dots, s,$$

we have from differentiation of (10) that

$$i_\sigma = C(v_\sigma) \frac{dv_\sigma}{dt}. \quad (11)$$

### 3. POWER-BASED DESCRIPTION FOR A CLASS OF MECHANICAL SYSTEMS

In (de Rinaldis and Scherpen, 2005) the authors enlarged the class of mechanical systems for which an electrical interpretation can be provided replacing the generalized coordinates vector  $(\dot{q}, q) \in \mathbb{R}^{2r}$  by the electrical states vector  $(i_\rho, v_\sigma) \in \mathbb{R}^{r+s}$ . In order to make the following relation a one-to-one mapping the equivalent circuit has to present a number of inductors  $r$  equal to the capacitors  $s$ . Moreover, all conservative forces acting on the masses should be (locally) invertible functions of its angular or linear position. The main result of (de Rinaldis and Scherpen, 2005) is as follows.

*Theorem 1.* Consider the general Lagrangian function (2). Assume that:

- A1** (*interconnection*)  $i_\rho = i_\sigma$ ,<sup>1</sup>
- A2** (*force-position link*)  $q_{\sigma j} = f_v^j(v_{\sigma j}) \in \mathcal{C}^1$  with  $j = 1, \dots, r$  is a set of invertible functions such that:

- $\frac{\partial f_v^j(v_{\sigma j})}{\partial v_{\sigma j}} = C_j(v_{\sigma j})$ ,
- $f_q^j(q_{\sigma j}) = v_{\sigma j}$ .

Then: the Euler-Lagrange (1) equations can be rewritten in terms of the Brayton-Moser framework as follows

$$\begin{bmatrix} -\tilde{D}(v_\sigma) - (\bar{D}(x) - \hat{D}(x))C(v_\sigma) \\ 0 & C(v_\sigma) \end{bmatrix} \dot{x} = \nabla P(x)$$

with

$$P(x) = -F(i_\rho) + G(v_\sigma) + i_\rho^T v_\sigma,$$

being the mixed potential function and where

$$\hat{D}(i_\rho, v_\sigma) = \begin{bmatrix} \frac{1}{2} i_\rho^T \frac{\partial D(q_\rho)}{\partial q_{\rho 1}}|_{q_\rho = f_v(v_\sigma)} \\ \vdots \\ \frac{1}{2} i_\rho^T \frac{\partial D(q_\rho)}{\partial q_{\rho r}}|_{q_\rho = f_v(v_\sigma)} \end{bmatrix} \quad (12)$$

$$C(v_\sigma) = \text{diag} \left( \frac{\partial f_v^j(v_{\sigma j})}{\partial v_{\sigma j}}, j = 1, \dots, r \right) \quad (13)$$

$$\tilde{D}(v_\sigma) = D(q_\rho)|_{q_\rho = f_v(v_\sigma)} \quad (14)$$

$$\bar{D}(i_\rho, v_\sigma) = \begin{bmatrix} a_{11}(i_\rho, v_\sigma) & \cdots & a_{1r}(i_\rho, v_\sigma) \\ \vdots & \ddots & \vdots \\ a_{r1}(i_\rho, v_\sigma) & \cdots & a_{rr}(i_\rho, v_\sigma) \end{bmatrix} \quad (15)$$

with  $a_{ij}(i_\rho, v_\sigma) = i_\rho^T C^{-1}(v_\sigma) \nabla_{v_\sigma} \tilde{D}_{ij}(v_\sigma)$  for  $i, j \in \{1, r\}$ .

*Corollary 1.* As a consequence of Theorem 1, recalling the definitions of the pseudo-inductor and the capacitor adopted in (9) and (11) respectively, the B-M equations can be then re-written in the following more compact form

$$\tilde{Q}(x) \dot{x} = \nabla P(x) \quad (16)$$

with

$$\tilde{Q}(x) = \begin{bmatrix} -\tilde{L}(v_\sigma) - \tilde{M}(i_\rho, v_\sigma) \\ 0 & C(v_\sigma) \end{bmatrix}$$

and where  $\tilde{L}(v_\sigma) = \tilde{D}(v_\sigma)$ ,  $\tilde{M}(i_\rho, v_\sigma) = (\tilde{D}(v_\sigma) - \hat{D}(i_\rho, v_\sigma))$ .

*Remark 1.* The former result can be interpreted in two ways. From one side we established under which conditions—A1 and A2—a mechanical systems described by EL equations, through derivation of an *energy-based* function called Lagrangian, has a clear electrical counterpart based

<sup>1</sup> Implying that  $s = r$  and  $\Lambda = I$ . See Remark 4 of (de Rinaldis and Scherpen, 2005) for the physical implications.

on the classical states analogy force/voltage and speed/current. On the other side, we state that this class of mechanical systems that can be electrically interpretable yields a *power-based* description in the BM framework. Under this second perspective we will present, in the further section, our main result.

### 3.1 Power-based passivity properties

This section is dedicated to the derivation of passivity *sufficient* conditions for that class of mechanical systems that admits the power-based description given in (16). For that we have to find a *storage function candidate* and a corresponding set of *port variables*. It is then instrumental for the derivation of the next theorem to re-define the mixed-potential function  $P(x)$  extracting the voltage sources  $v_s \in \mathbb{R}^l$  with  $l \leq r$ , from the content term  $F(i_\rho)$  as follows

$$P(x) = \tilde{P}(x) - x^T B v_s \quad (17)$$

with  $B = (B_s, 0)^T$  and  $B_s \in \mathbb{R}^{r \times l}$ .

*Remark 2.* In equation (4) we restricted our analysis to circuits having only voltage sources in series with inductors. This choice seems to be sensible considering that the mechanical counterpart of a current source is a velocity source which have no clear sense from a physical view point.

**3.1.1. Storage function candidate** Following the procedure of (Jeltsema *et al.*, 2003), we can pre-multiply (16) by  $\dot{x}^T$  obtaining

$$\dot{x}^T \tilde{Q}(x) \dot{x} = \dot{x}^T \nabla_x \tilde{P}(x) - \dot{x}^T B v_s$$

that can be re-arranged as follows

$$\frac{d\tilde{P}}{dt}(x) = \dot{x}^T B v_s + \dot{x}^T \tilde{Q}(x) \dot{x} \quad (18)$$

which consists of the sum of two terms. The first one represents the inner product of the source variables in the suited form  $\dot{x}^T B v_s = v_s^T \hat{i}_s$ , where we assume the vector  $i_s \in \mathbb{R}^l$  indicating the correspondent current terms flowing from each inductor series-connected voltage source. The second one is a quadratic term. In general  $\tilde{Q}(x)$  is not symmetric and its symmetric part is sign indefinite making difficult the derivation of the power-balance inequality we are looking for. In order to overcome this drawback we follow the same procedure exploited in (Jeltsema *et al.*, 2003), (Brayton and Moser, 1964), (Ortega *et al.*, 2003) that basically provides a method to describe the system

(16) by another admissible pair, say  $\tilde{Q}_a(x)$  and  $P_a(x)$ . For instance, if the new pair fulfills the following conditions:

$$\mathbf{C1} \quad \tilde{Q}_a^T(x) + \tilde{Q}_a(x) \leq 0$$

$$\mathbf{C2} \quad \tilde{P}_a(x) : \mathbb{R}^{s+r} \rightarrow \mathbb{R} \text{ is positive semi-definite scalar function}$$

we may state that

$$\frac{d\tilde{P}_a}{dt}(x) \leq \dot{x}^T B v_s \quad (19)$$

being  $\tilde{P}_a(x)$  the storage function candidate related to  $P_a(x)$  by (17), the pair  $(v_s, \hat{i}_s)$  is a passive pair and can serve as port-variables.

**3.1.2. Power-balance inequality and passivity requirements** In the next theorem we will provide some conditions for passivity that may be useful for control in the power-based framework. In particular, we refer to a previous work of the second author (Jeltsema *et al.*, 2003) where the storage function has the dimension of power and is defined as a re-shaped mixed potential function  $P_a(x)$ . This new function is then related to a new matrix  $\tilde{Q}_a(x)$  and both, having common solutions for (16), are related to the original pair  $\tilde{Q}(x), P(x)$  by the following relations<sup>2</sup>

$$\begin{aligned} \tilde{Q}_a(x) &= \left[ \frac{1}{2} \nabla^2 P(x) \Pi(x) \right] Q(x) \\ &\quad + \left[ \frac{1}{2} \nabla(\nabla^T P(x) \Pi(x)) + \lambda I \right] Q(x) \\ P_a(x) &= \lambda P(x) + \frac{1}{2} \nabla^T P(x) \Pi(x) \nabla P(x) \end{aligned}$$

with  $\Pi(x) \in \mathbb{R}^{r \times r}$  a symmetric matrix and  $\lambda \in \mathbb{R}$  any constant.

*Theorem 2.* Consider an electrical system for which the dynamics is described by (16) and assume A1 and A2 hold. Moreover, Assume that

**A3** (*positivity*) pseudo-inductors and capacitors matrices are positive definite

**A4** (*linearity in the content*)

$F(i_\rho) = -(1/2) i_\rho^T R_\rho i_\rho > 0$ , i.e., the current-controlled resistor matrix  $R_\rho$  is constant and positive definite

**A5** (*damping condition*)<sup>3</sup>

$$\left\| 2R_\rho^{-1} \tilde{M} C^{-1} + \tilde{M}^T \tilde{L}^{-1} \tilde{M} C^{-1} + \beta \right\| \leq 1$$

<sup>2</sup> See (Ortega *et al.*, 2003) for a detailed proof of this statement.

<sup>3</sup> For a matter of notation, from now on the arguments of each matrix term will be missing in purpose. Anyway, we remind that  $\tilde{M} = \tilde{M}(x)$ ,  $\tilde{L} = \tilde{L}(v_\sigma)$  and  $C = C(v_\sigma)$ .

with

$$\beta := \beta(x) = \frac{\partial}{\partial v_\sigma} \left( i_\rho^T \tilde{L} R_\rho^{-1} C^{-1} \right).$$

**A6** (technical assumption)

$$\tilde{L} R_\rho^{-1} C^{-1} \geq 0$$

then

$$\int_0^t v_s^T(t') \frac{di_s}{dt'} dt' \geq \tilde{P}_a(x(t)) - \tilde{P}_a(x(0)). \quad (20)$$

*Proof.* First, we set the matrix  $\Pi(x)$  and the scalar  $\lambda$  in order to guarantee the semi-definite positivity of the storage function  $P_a(x)$  and to satisfy the following requirement <sup>4</sup>

$$\tilde{Q}_a(x)^T + \tilde{Q}_a(x) \leq 0 \quad (21)$$

Define

$$\lambda = -1, \\ \Pi(x) = \text{diag}(2R_\rho^{-1}, 2\tilde{L} R_\rho^{-1} C^{-1}).$$

Considering a mixed potential function  $P(x)$  fitting the Assumption A4 and reminding that Assumption A1  $\Rightarrow \Lambda = I$ , we obtain

$$\tilde{Q}_a(x) = \begin{bmatrix} -\tilde{L} & -\tilde{M} - 2\tilde{L} R_\rho^{-1} \\ 2R_\rho^{-1} \tilde{L} & -(I - \beta)C + 2R_\rho^{-1} \tilde{M} \end{bmatrix}$$

that, under Assumptions A3 and A5, satisfies (21). We refer to the appendix for a detailed development of the former statement. Furthermore, the storage function candidate becomes

$$\tilde{P}_a(x) = \frac{1}{2} (R_\rho i_\rho + v_\sigma)^T R_\rho^{-1} (R_\rho i_\rho + v_\sigma) + \frac{1}{2} v_\sigma^T R_\rho^{-1} v_\sigma + i_\rho^T \tilde{L} R_\rho^{-1} C^{-1} i_\rho \quad (22)$$

which, under Assumption A6, is clearly positive definite.  $\triangleleft$

*Remark 3.* Assumption A5 is an important condition that can be satisfied with *small* values of the matrix  $R_\rho^{-1}$ —which represent the LTI resistors placed in series to each inductor— and/or with a *weak* mutual-coupling action provided by the presence of the matrix  $\tilde{M}(x)$ . Since  $\tilde{M}(x)$  depends linearly on the current vector  $i_\rho$ —see  $\tilde{M}(x)$  definition provided in Theorem 1—, we can state that for *slow motion* or *well-damped* dynamics, A5 holds.

<sup>4</sup> If these two conditions are matched the overall system, for which the dynamics can be written as  $\tilde{Q}^{-1}(x) \nabla P(x) = -\tilde{Q}^{-1}(x) \nabla P_a(x) = (di_\rho/dt, dv_\sigma/dt)^T$ , is then asymptotically stable.

#### 4. THE INVERTED PENDULUM ON A CART

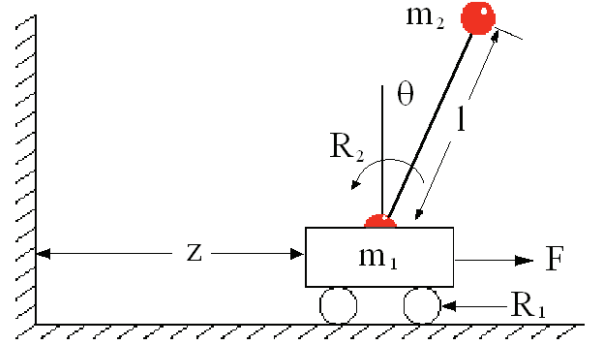


Fig. 1. Inverted pendulum on a cart.

An interesting example of mechanical system to study is the inverted pendulum with rigid massless rod (of length  $l$ ) placed on a cart as shown in Fig. 1. It is often used to test the performance of controllers that stabilize the pendulum mass  $m_2$  to its natural unstable equilibrium point through a force  $F$  acting just on the cart of mass  $m_1$ . The equations describing the dynamics of the masses could be computed considering as state variables the angular position of the rod with the vertical axis  $\theta$  and the cart distance  $z - z_0$  to a fixed reference ( $z_0 = 0$ ). The motion dynamic of each mass can be determined via the Euler-Lagrange equations

$$(m_1 + m_2)\ddot{z} + m_2 l \cos \theta \ddot{\theta} - m_2 l \sin \theta \dot{\theta}^2 = F - R_1 \dot{z} \\ m_2 l^2 \ddot{\theta} + m_2 l \cos \theta \ddot{z} - m_2 g l \sin \theta = -R_2 \dot{\theta} \quad (23)$$

where the generalized coordinates related to the position of each mass are  $q = (z, \theta)^T$  and its derivative  $\dot{q} = (\dot{z}, \dot{\theta})$  representing the corresponding velocities. Applying the following coordinates transformation <sup>5</sup>

$$\begin{bmatrix} z \\ \theta \end{bmatrix} = \begin{bmatrix} C_1 v_{\sigma 1} \\ f_2^v = \arcsin \left( \frac{v_{\sigma 2}}{K} \right) \end{bmatrix}, \quad (24)$$

$$\begin{bmatrix} \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} i_{\rho 1} \\ i_{\rho 2} \end{bmatrix} \quad (25)$$

with  $K = m_2 g l$  and considering that Assumptions A1 and A2 are clearly satisfied we can express the motion equations (23) via the Brayton-Moser framework

<sup>5</sup> The relation  $(\dot{q}, q) \Leftrightarrow (i_\rho, v_\sigma)$  is one-to-one only when  $\theta$  belongs to the open interval  $(-\frac{\pi}{2}, \frac{\pi}{2})$ .



$$\tilde{Q}(x)\dot{x} = \nabla P(x) \quad (26)$$

with  $\tilde{Q}(x)$  easily obtained from (23) and  $C_1 \in \mathbb{R}_+$  an arbitrary constant. Now that we have expressed the mechanical system model by (26) we can use the Theorem 2 in order to get the explicit passivity condition. By choosing

$$\lambda = -1, \quad \Pi(x) = \text{diag}(2R^{-1}, 2\tilde{L}R^{-1}C^{-1}),$$

after some algebraic computations we get the final local condition

$$\left\| \begin{array}{cc} 0 & \frac{1}{R_1} 2l \sin f_2^v i_{\rho 2} \\ \frac{(l \sin f_2^v)^2}{\frac{m_1}{m_2} + 1 - \cos^2 f_2^v} - \frac{i_{\rho 1} m_2 l \sin f_2^v C_2 (v_{\sigma 2})}{i_{\rho 2} R_2} & \end{array} \right\| \leq 1 \quad (27)$$

achieved for  $C_1 \rightarrow \infty$ . The former suitable choice of  $C_1$  parameter is arbitrary because it depends on the coordinates transformation we arbitrary fixed. Of course, in order to apply theorem 2 we have to verify, together with condition (27), that Assumption 6 holds, that means

$$\left\| \begin{array}{cc} 0 & m_2 l \cos f_2^v \\ m_2 l \cos f_2^v & m_2 l^2 R_2^{-1} C_2^{-1} \end{array} \right\| \geq 0 \quad (28)$$

From the overlap of (27) and (28), we deduce a local condition for which

$$\int_0^t F \dot{i}_{\rho 1}(\tau) d\tau \geq \tilde{P}_a(t) - \tilde{P}_a(0)$$

with  $\tilde{P}_a(x)$  given by (22), holds.

## 5. CONCLUSION AND OUTLOOKS

Our main purpose in this document was to present an alternative way to describe the dynamics of a large class of (possibly non-)linear mechanical systems within a framework—the Bryton-Moser equations—that relates the power to the trajectories of the system instead of energy, and derive from it sufficient conditions for passivity. This should be consider as a preliminary step towards stabilization of mechanical and electromechanical systems using passivity arguments—as already suggested in (Ortega *et al.*, 2003)—.

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## Appendix

Here, we show that given Assumptions A3 and A5 of Theorem 2, the positivity of  $Q_a(x)$  is established, i.e., (21) holds. Indeed, computing the symmetric part of  $Q_a(x)$  we have

$$H_a(x) = \begin{bmatrix} \tilde{L} & \tilde{M} \\ \tilde{M}^T & (I - \beta)C - 2R_\rho^{-1}\tilde{M} \end{bmatrix}.$$

Then, provided the positivity of  $\tilde{L}(v_\sigma)$  by A3, we compute the Schur's complement of  $H_a(x)$  and imposing his positivity we obtain

$$(I - \beta)C - 2R_\rho^{-1}\tilde{M} \geq \tilde{M}^T \tilde{L}^{-1} \tilde{M}$$

Let's re-write the above inequality as follows

$$I \geq 2R_\rho^{-1}\tilde{M}C^{-1} + \tilde{M}^T \tilde{L}^{-1} \tilde{M}C^{-1} + \beta,$$

as a consequence of Perron's theorem<sup>6</sup> and reminding that the spectral norm applying on any squared matrix  $A \in \mathbb{R}^{r \times r}$  is defined as

$$\|A\| = \sqrt{\rho(A^T A)}$$

we have

$$1 \geq \left\| 2R_\rho^{-1}\tilde{M}C^{-1} + \tilde{M}^T \tilde{L}^{-1} \tilde{M}C^{-1} + \beta \right\|$$

which is true by Assumption A5.

<sup>6</sup> See lemma 8.4.2 of (Horn and Johnson, 1985).